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SOME ASPECTS OF ELECTRONIC SURVEYING

By Carl I. Aslakson, M. ASCE

SURVEYING AND MAPPING DIVISION

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PAPERS

SOME ASPECTS OF ELECTRONIC SURVEYING

By Carl I. Aslakson,[1] M. ASCE

Synopsis

Although the earliest attempts to test electronic instruments for use in surveying and mapping began as recently as the latter stages of World War II, much has been accomplished in a brief time. Electronic instruments have been used or tested in the following surveying fields:

1. Hydrographic surveying;
2. Airborne magnetometer surveys;
3. Measurement of long distances for geodetic control purposes;
4. Photogrammetry, in which their application is twofold:
   a. Accurate flight-line navigation, and
   b. Geodetic control of individual photographs;
5. Measurement of short distances—that is, distances ordinarily associated with conventional ground triangulation;
6. Topographic surveying for both distance and direction measurements; and
7. Vertical control in photogrammetry.

Clearly all branches of surveying and mapping are being influenced by these new developments. The purpose of this paper is to review these aspects of electronic surveying practices.

Hydrographic Surveying

Electronic surveying equipment was adopted in hydrographic surveying with scarcely the formality of a test period in that field. Shoran, for example, was tested by the United States Coast and Geodetic Survey, and the first field trial developed into a well-controlled hydrographic survey. Originally a blind-bombing instrument, it was used for hydrography without modification.

Note—Written comments are invited for publication; the last discussion should be submitted by July 1, 1951.

[1] Comdr., U. S. Coast and Geodetic Survey, Washington, D. C.

Because of its transmission frequency of from 220 millicycles per sec to 350 millicycles per sec, shoran is limited in range. Electromagnetic waves of this frequency are propagated in nearly the same manner as light, and hence the range is limited to "line of sight." With moderate shore antenna heights of from 50 ft to 100 ft, the effective shoran range of the survey vessel is from about 30 miles to 40 miles. The necessity of extending this range led the Coast and Geodetic Survey to develop the "Electronic Position Indicator," commonly known as the EPI. Designed to use a frequency of 1,850 kilocycles per sec, the signals can be propagated for long distances by the "surface wave." The British Decca was designed for a frequency of 100 kilocycles per sec and is also a long-range hydrographic instrument. Some accuracy is sacrificed when lower frequencies are used, but hydrographic surveys can be extended hundreds of miles beyond the limits of shoran with a smaller positional error than is inherent in any previously known method.

Therefore it may be stated that electronic surveying methods have already revolutionized hydrographic surveying and that advances are continuing.

Airborne Magnetometer Surveys

Soon after the end of World War II, commercial organizations secured shoran equipment for controlling airborne magnetometer surveys. Previously no method of plotting flight lines over water or unmapped areas with the accuracy required for these magnetometer surveys was known. Up to the present time, numerous successful magnetic surveys have been completed, and valuable geophysical information has been compiled. Continued use of electronic positioning equipment for geophysical surveying is assured.

Measurement of Long Distances

Because shoran and other similar instruments were designed for positioning bombers over their targets, the possible application of these methods to long-distance measurement immediately attracted the geodesist. The possibilities of making intercontinental and interisland ties where distances were too great for conventional optical methods, and of making measurements over inaccessible terrain, inspired geodesists to undertake several test projects. The most important question to be answered was: "Can long distances be measured with geodetic accuracy by electronic instruments?"

The most extensive of these test programs was begun in 1944 by the United States Army Air Forces under the direction of the writer. Two comprehensive projects were undertaken which were concluded in 1947. Considering the fact that these tests were based on using a modified blind-bombing instrument instead of one designed for surveying, the results obtained were remarkable. Because certain cyclic or "repeating" errors inherent in the system could not be completely eliminated by design modifications, it was necessary to design observational techniques to minimize them. This approach was highly successful, and in the latter phase of the project forty-seven distances which varied between 67 miles and 367 miles were measured in the Caribbean area.

A complete discussion of the technique is beyond the limits of this paper, but the problems that faced the project staff were so extensive that the methods designed to overcome them will be described briefly.

As previously stated, the high frequencies necessary for greater accuracy are propagated on line-of-sight paths. Range is therefore limited by curvature of the earth and local obstructions. However, the equipment is adapted for installation in aircraft, making the range a function of airplane altitude when no local obstructions exist near the ground stations. When an airplane is flying at an altitude of 40,000 ft, shoran or similar instruments can measure a distance of more than 250 miles between the aircraft transceiver and ground station transponder. Using two ground transponders the effective measuring range is doubled. This result is accomplished by flying the airplane across the line between the stations, recording simultaneously at short intervals the distances to both ground staitons and determining the minimum sum distance graphically or analytically. The minimum sum distance can be corrected to the geodetic distance by geometrical corrections involving plane altitude, ground station altitudes, and the radius of the earth.

Using long distances measured in the foregoing manner, a trilateration scheme can be executed by which geographic positions can be carried forward on a known datum.

The Carribbean tests proved that the method was practical. A board of experts appointed to evaluate the results concluded that:

(1) Accuracy approaching second order was attained; and

(2) Evidence of a possible error in the accepted value of the velocity of propagation of radio waves was present. If true, this would increase the estimated accuracy.

In accordance with the second comment by the board, the writer made an investigation of the velocity of radio waves as indicated by the shoran results. The deduced velocity of electromagnetic waves in vacuo was found to be 299,792 km per sec or 16 km per sec greater than the previously accepted value.[2] Further evidence that this uncertainty exists is shown by the results of two other observers, L. Essen[3] in England and Erik A. Bergstrand[4] in Sweden, both of whom have obtained substantially the same value by independent methods. Obviously, further research in determining this important constant is necessary before electronic systems of measuring long distances can be evaluated properly.

The operational procedure and computational methods of shoran trilateration at first appear so laborious as to be impractical, but experience has proved otherwise. The flight maneuvers are operationally practicable and the necessary computational steps can be arranged in an orderly manner. The computations can be so simplified that relatively inexperienced computers can perform the mass calculations. Extensive use of tables expedites the computations. The following fundamental steps are required to determine the geodetic distances and the final geographic positions:

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[2] "Can the Velocity of Propagation of Radio Waves Be Mesaured by Shoran?" by Carl I. Aslakson, *Transactions*, Am. Geophysical Union, August, 1949, p. 475.

[3] "Velocity of Electronic Waves," by L. Essen, *Letter in Nature*, London, England, Vol. 195, 1947, No. 4044, p. 611.

[4] "A Preliminary Determination of the Velocity of Light," by Erik A. Bergstrand, *Kunglige Svenska Vetenskapsakadmien*, Vol. 36A, Stockholm, Sweden, No. 20, 1948.

(*a*) Determination of minimum sum distances and altitudes of aircraft and ground stations;
(*b*) Application of instrumental calibration corrections;
(*c*) Determination of velocity corrections;
(*d*) Application of geometrical corrections;
(*e*) Least-squares adjustment of the net work of trilateration; and
(*f*) Computation of the geographic positions.

Determination of Minimum Sum Distances

In practice the equation of the time intervals (or frame numbers) versus sum distances is considered as a parabola. This assumption is not exactly true but it can be shown that for the conditions under which the lines are flown no appreciable error accrues from making it. The observed distances, as read from the film of the automatic recorder, are added and a parabola is fitted to the observations by a least-squares adjustment. Extensive use is made of precomputed constants to shorten the operation. The minimum value on the vertex of the computed parabola is the desired sum distance, representing all observations made during the line crossing. A graphical plot of observed sum distance versus frame number, and the corresponding fitted parabola, is shown in Fig. 1.

Simultaneously with the line-crossing measurements the aircraft altitude is determined by one or more of several methods involving the use of radio altimeters, barometric altimeters, and meteorological observations. The ground station elevations are determined by conventional methods.

The line-crossing procedure, known as the "figure-eight method" is shown in Fig. 2. The purpose of adopting this flight procedure is to eliminate or minimize observer's errors and certain instrumental errors of a repeating nature. Approximately 1 mile of distance change for each station is used for the computation, the reason being that the instrument has a cyclic error that repeats itself each mile. The observing procedure also eliminates errors caused by slackness in certain gear trains and minimizes the personal errors of observers in tending to lead or lag as they make coincidences between moving "pips" on the oscilloscope.

Instrumental Calibration Corrections

Certain instrumental corrections must be determined by calibration and applied to the minimum distances. The most important of these are crystal frequency calibrations, measurements of some fixed delays in component parts of the equipment, a zero or an index correction, and an empirical correction for an error which results from varying signal intensities.

Velocity Corrections

Shoran equipment must be designed for a constant velocity of propagation which is fixed in the instrument by a crystal of a given frequency. However, the radio waves travel through air of varying pressure, temperature, and moisture content which change the velocity along the path. Therefore it is necessary to adjust each distance by a correction which is a function of the difference

between the assumed and actual conditions. The lapse rates of pressure, temperature, and relative humidity along the ray path can be determined in a number of ways, but the best method is to use a second airplane to make the

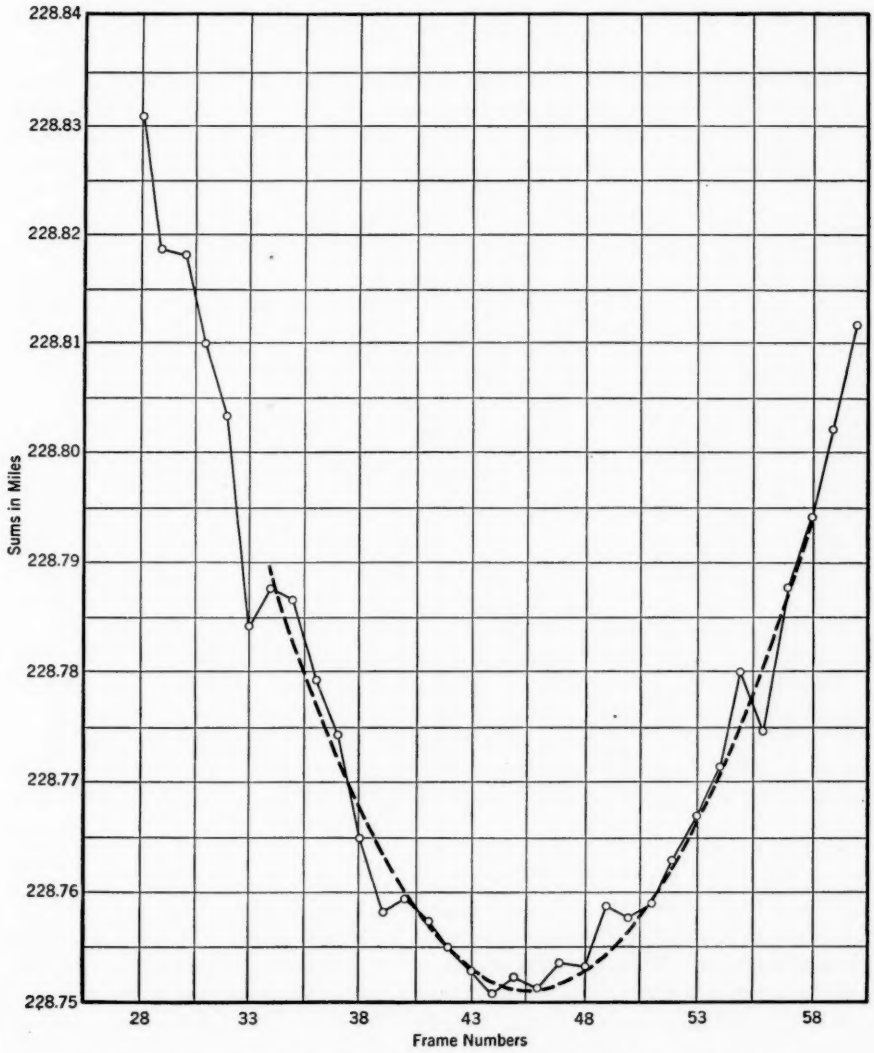

FIG. 1.—GRAPHICAL PLOT OF OBSERVED SUM DISTANCES VERSUS FRAME NUMBERS, AND THE CORRESPONDING FITTED PARABOLA

meteorological measurements. It can be shown that the velocity correction can be expressed satisfactorily by the following relationship:

$$\Delta S = \int_0^S \Delta n \, ds \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which ΔS is the velocity correction; S is the shoran distance; and Δn is the difference between the index of refraction assumed in the instrument design and the index of refraction at a point on the ray path corresponding to the distance s. In practice the integration is made numerically.

Geometrical Corrections

The computed minimum distances must be reduced to the geodetic distance by corrections based on the distance, altitude of aircraft, and altitude of

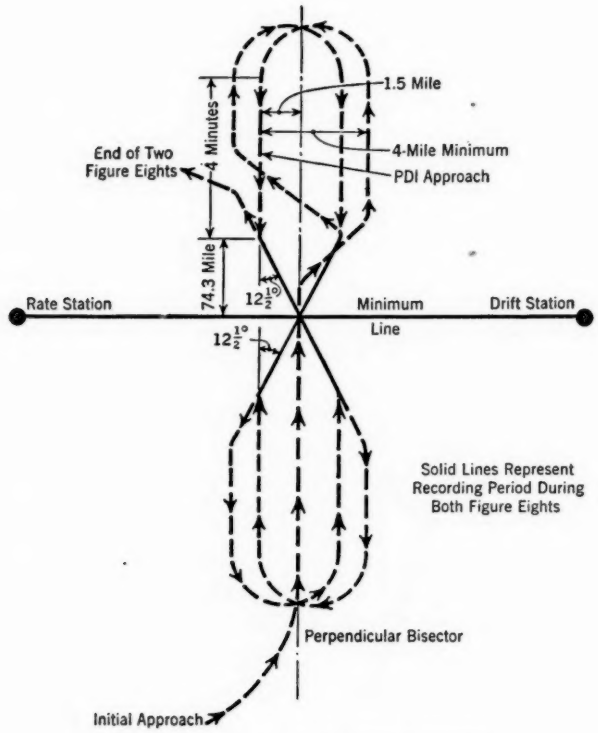

Fig. 2.—Shoran Line-Crossing Procedure

ground stations. The general equation of the corrected distance is

$$M = 2\,R_\alpha \arcsin \sqrt{\frac{4\,r^2 \sin^2 (S/2\,r) - (H - K)^2}{4\,(R_\alpha + H)\,(R_\alpha + K)}} \quad \ldots\ldots\ldots (2)$$

in which M is the geodetic distance; R_α is the radius of the earth at the point of the line crossing along the azimuth of the line; r is the mean radius of curvature of the shoran ray; S is the shoran distance as observed; H is the altitude of the aircraft; and K is the altitude of the ground station. The assumption that the ray path is a circular curve causes a small error which can be removed by a correction table since the actual ray path can be determined with moderate

accuracy from the meteorological observations. The error resulting from the assumption that the length of the "geodesic" is equal to the length of the plane curve is negligible.

In actual practice the use of the rigid formula (Eq. 2) is not justified. Several simpler relationships are currently in use and are sufficiently accurate for all practical purposes.

Cedric W. Kroll[5] has developed a rigorous method of computing the velocity correction and geometrical correction simultaneously by numerical integration of the basic differential equation of refraction along the ray path. This method is too laborious to use unless electronic computing instruments are available.

Adjustment of Shoran Trilateration

A network of shoran-measured distances can be adjusted easily by the method of least squares if observation equations are used. The general form of the observation equation is

$$S_{pq} + V_{pq} = - X_p \sin \alpha_{pq} + Y_p \cos \alpha_{pq} - X_q \sin \alpha_{qp} + Y_q \cos \alpha_{qp} + i_{pq} + K \ldots (3)$$

in which S_{pq} is the observed shoran distance; V_{pq} is the most probable change in S_{pq}; X_p and Y_p are the changes in the abscissa and the ordinate of P; X_q and Y_q are the corresponding changes in Q; α_{pq} and α_{qp} are the geodetic azimuths at P and Q, respectively; i_{pq} is the inverse distance computed from the assumed positions of P and Q; and K is a constant which represents a constant error in each measurement. The constant K need not be introduced unless the presence of such an error is suspected.

The assumed positions can be determined by computing geographic positions through a single chain of triangles using first-order geographic position forms. The next step consists of computing rigid inverse distances between all points over which shoran distances are measured to obtain the values of i_{pq}.

The general equation may be rearranged as necessary to fit specific conditions such as those when certain points, distances, and azimuths have to be held fixed. The observation equations are then reduced to normal equations and are solved by conventional methods.

Computation of Geographic Positions

The rigorous computation of geographic positions is difficult when long lines are involved. When the aforementioned adjustment method is used, the position computation is simple. After the adjustment is completed, it merely becomes necessary to change the assumed positions by the X-value and the Y-value as derived from the adjustment. Obviously this method does not furnish azimuths; but they can be computed by inverse computations if required. In practice, azimuths will seldom be required in long-line trilateration.

Advantages of Shoran Trilateration

Long-distance electronic trilateration has certain advantages that may assume great importance in surveying and mapping:

[5] "A Rigorous Method for Computing Geodetic Distance from Shoran Observations," by Cedric W. Kroll, *Transactions*, Am. Geophysical Union, February, 1949, p. 1.

(1) Distances of more than 500 miles can be measured—greatly exceeding distances which can be measured directly by conventional methods.

(2) When the time factor is important, the rapidity with which shoran surveys can be made may be the controlling factor in determining its adoption. It has been demonstrated that large areas can be surveyed in a few months which could not be surveyed in decades using conventional methods.

(3) The functions of geodetic control and aerial photography can be combined efficiently in a single organization, and these operations can be performed simultaneously on the same project.

(4) Unit area costs are far lower than those of conventional methods of control. A satisfactory estimate of the cost of shoran geodetic control is about $1.00 per sq mile. This estimate is derived from a single large shoran project. The cost per station is large, but few stations are required for comprehensive surveys.

Electronic Distance Measurement in Photogrammetry

There are two important applications of electronic distance-measuring equipment in photogrammetry:

(*a*) Shoran or similar instruments provide the most efficient method of flight-line navigation that has been developed; and

(*b*) Shoran distances can be recorded for every aerial photograph, providing the third-order control simultaneously with aerial photography.

Flight-Line Navigation

Conventional navigation of photogrammetric airplanes is always difficult even when good maps are available. Over water or uncharted areas excessive side lap is required, and even then many gaps occur which necessitate costly reflights. When shoran is available, flight-line navigational instruments can be used to simplify airplane navigation greatly. These instruments, operating directly from the shoran mileage counters, indicate the position of the aircraft with respect to a given flight line at all times. In fact, a pilot-direction indicator shows this relationship in unit changes of about 25 ft. Several designs of these flight-line indicators have been operated successfully with large savings resulting from reduction in overlap, avoidance of gaps, and reduced cost of compilation.

Control of Aerial Photographs

The British have tested their electronic instruments Oboe, G-H, and Decca for control of aerial photographs. An official British report has stated:

> "Although maps at 1–25,000 to 1–50,000 can be made to a reasonable standard of accuracy without direct reference to the ground, mapping to full peacetime specifications at present requires a small amount of ground control when radar fixes are employed but on a very much reduced scale."

The only published estimate of the accuracy of shoran is based on early tests. The Engineer Research and Development Laboratories, at Fort Belvoir, Va., estimate that:

1. Random errors amounting to 120 ft are encountered in individual sheets of 1:50,000 compilations; and

2. In addition, systematic errors of about 40 ft may occur between sheets. Studies of recent projects, particularly those where the flight-line navigator was used, may reduce these estimates.

Clearly, electronic control of aerial photographs approaches the accuracy afforded by the slow and costly conventional ground control. Certainly the present accuracy is adequate for many areas which are now unmapped. The advantages of mapping entirely by electronic control are very great in that:

a. Less time is lost due to weather;
b. Unit costs are low;
c. Inaccessible terrain can be mapped; and
d. Large areas can be mapped very quickly.

Efficient Use of Weather

Continuously good photographic weather is rare. Frequently photographic airplanes remain on the ground for long periods when flying conditions are good but cloud coverage is too great for photography. All this time can be used in line measurement for the geodetic control. When, at last, photographic weather prevails, the mission can be changed to photography. Clouds, haze, smoke, and fog do not prevent shoran-distance measurement. Obviously a combination of both these functions contributes toward efficiency.

Unit Costs of Combined Operations

Aside from the reduction in cost of geodetic control, shoran photography should prove to be cheaper than photography flown with conventional navigation because of the efficiency of the flight-line navigation system. No appreciable gaps requiring reflights have thus far been encountered on any shoran-navigated project. At the same time the side lap can be reduced to the minimum amount required by the compiler. On numerous occasions, flight lines abandoned because of the presence of cloud banks have been continued at a later date exactly where the break occurred. Logistical costs are decreased because location of control station is very flexible. Airfields often provide good sites for shoran ground stations. Observers who have seen shoran-controlled photography in use are enthusiastic supporters.

Mapping of Inaccessible Terrain

The facility with which inaccessible mountains, jungle, tundra, or swamps can be mapped by shoran control is most important. For example, frequently a mountain range may be mapped without establishing a single shoran station on a mountain peak. Fig. 3 shows a typical hypothetical shoran scheme in the Appalachian Mountains. Examination of Fig. 3. will show that the distance measurements can be made on or near the centers of each line and that careful location of the stations on local prominences outside the mountain range will provide all needed control. Furthermore, the same stations provide shoran control for a large area on both sides of the trilateration scheme.

Examination of Fig. 3 will show a number of long thin triangles. The deliberate incorporation of these slim triangles into a scheme is an interesting feature of shoran trilateration. Their purpose is to reveal the possible presence of constant errors of measurement. This may be clarified by stating that, if a line is measured as a whole by shoran and if a second measurement is derived from projection of the two shorter sides, a constant error occurring in each single measurement would equal the difference between the long measurement

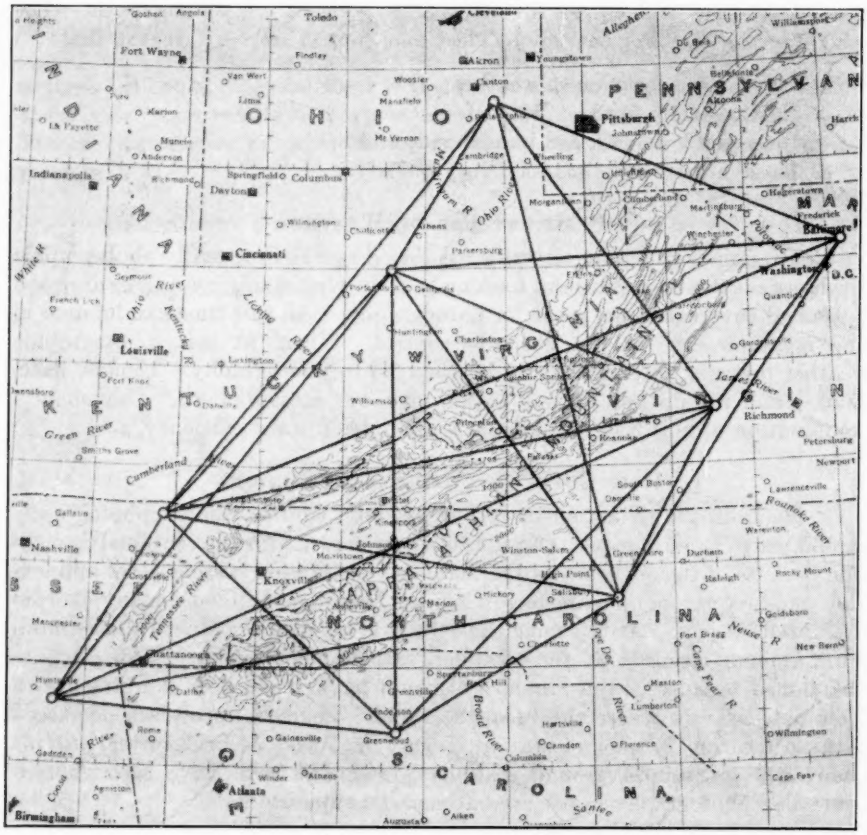

FIG. 3.—TYPICAL SHORAN FIGURES

and the sum of the two short measurements. Consequently, the presence of a constant error in each shoran measurement would be revealed in the adjustment when a number of thin triangles is included in the network.

SPEED OF SHORAN SURVEYS

The rapidity with which shoran-controlled photography can be executed has been proved repeatedly in practice. In one case, an area of 36,000 sq miles was photographed which had previously remained unmapped in spite of the

efforts of several years to photograph it with conventional navigation. No time is lost in beginning flight lines. The shoran straight-line navigator enables the photographic plane to be flown directly to the starting point of each flight line. Small open areas free from cloud coverage can be photographed efficiently even though the flight lines are short. Time lost because of weather is therefore reduced to a miminum.

Frequently, the time element is more important than all other considerations. Mineral discoveries, economic development, or military requirements may demand rapid mapping of large areas where no control exists. At present, makeshift reconnaissance maps or uncontrolled mosaics must suffice. In such areas electronically-controlled aerial photography will quickly provide unified and controlled maps with reasonable accuracy.

Short-Distance Measurement by Electronic Methods

The field of ordinary ground surveying is also being invaded by electronic surveying methods. Here competition is keen because one advantage of the electronic long-range equipment is its capacity to obtain results where conventional methods fail. However, even in ground surveying it is now safe to predict that many electronic surveying instrments will soon be in use. At present many are being developed and a few descriptions have been published.

One electronic distance measuring instrument which is very promising has been developed in Sweden. The "Bergstrand geodimeter" uses light reflected from a plane mirror target. The light is modulated in precisely controlled waves which are picked up by a photo cell after reflection from the target. Space limitations prevent a detailed description of this instrument, but published reports claim that accuracy greater than 1 part in 300,000 can be attained with this instrument over distances up to 30 km. The time required for an observation is reported to be two hours, with two additional hours required for computation of the results. The instrument is reported to be portable, and adaptable to field use. Observing conditions required are similar to those needed for conventional triangulation.

Several other portable field instruments using visible light or high radio frequencies have been designed or are under development. The principles differ widely but many of them are very promising.

As an example of an efficient use of instruments of this type reference is made to Figs. 4 and 5. Fig. 4 shows a conventional scheme of river triangulation used by the United States Coast and Geodetic Survey. Between line A and line B there is a total of fifty-one stations. Fig. 5 shows how this scheme can be reduced to twenty-five stations and great strength of figure can be maintained by measuring the heavy lines with an instrument similar to the geodimeter. Azimuth checks can be carried accurately through the scheme of triangles and, at the same time, checks on the electronically-measured bases are possible from the thin triangles. Certainly the surveying engineer must soon learn to revise his conception of "strength of figure."

Topographic Surveying

At least one electronic system promises to be useful in topographic surveying. The Engineers Research and Development Laboratories have published a description[6] of an electro-optical system that measures distance by light pulses

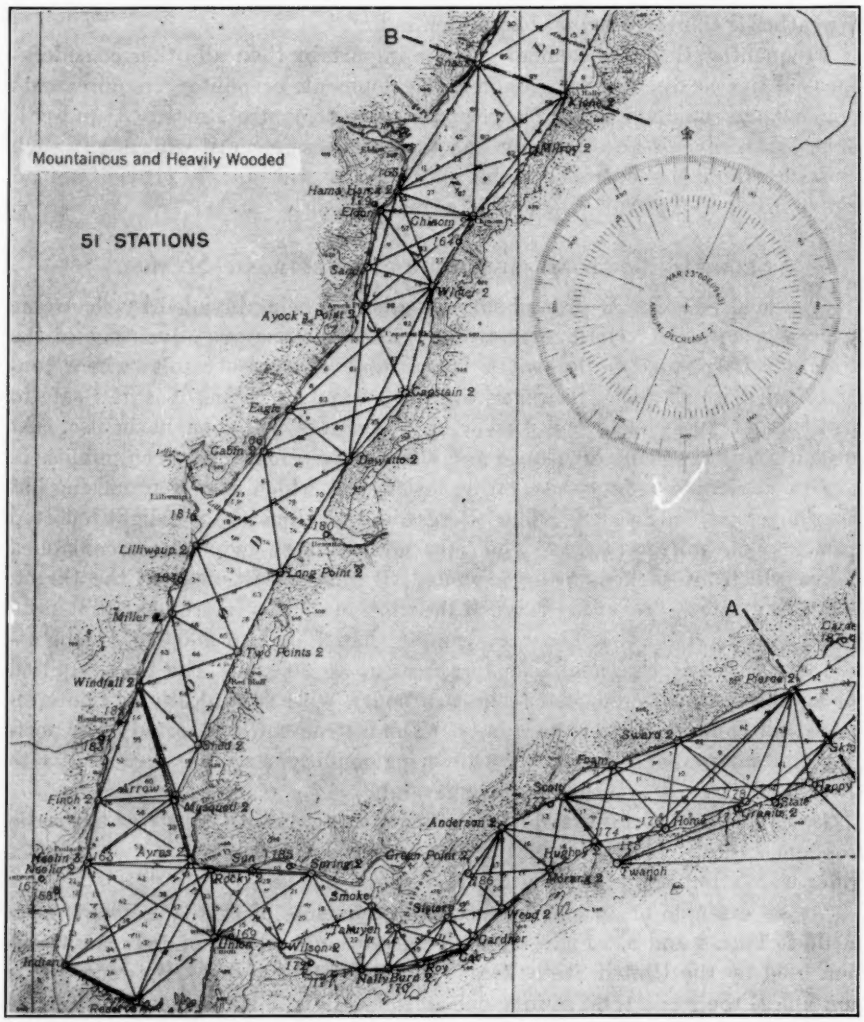

Fig. 4.—Typical Conventional Scheme of River Triangulation

with an accuracy of about 1 part in 2,500. This instrument also measures both horizontal and vertical angles to about 1 min of arc. The system is portable, easy to use, and has a range of about 3 miles. The target is a corner

[6] "Development of an Optical Radar System," by Charles A. Hoover, *Transactions*, Am. Geophysical Union, August, 1950.

cube reflector. The use of such an instrument may be important in small topographic surveys, aerial photograph control, and low-order triangulation schemes.

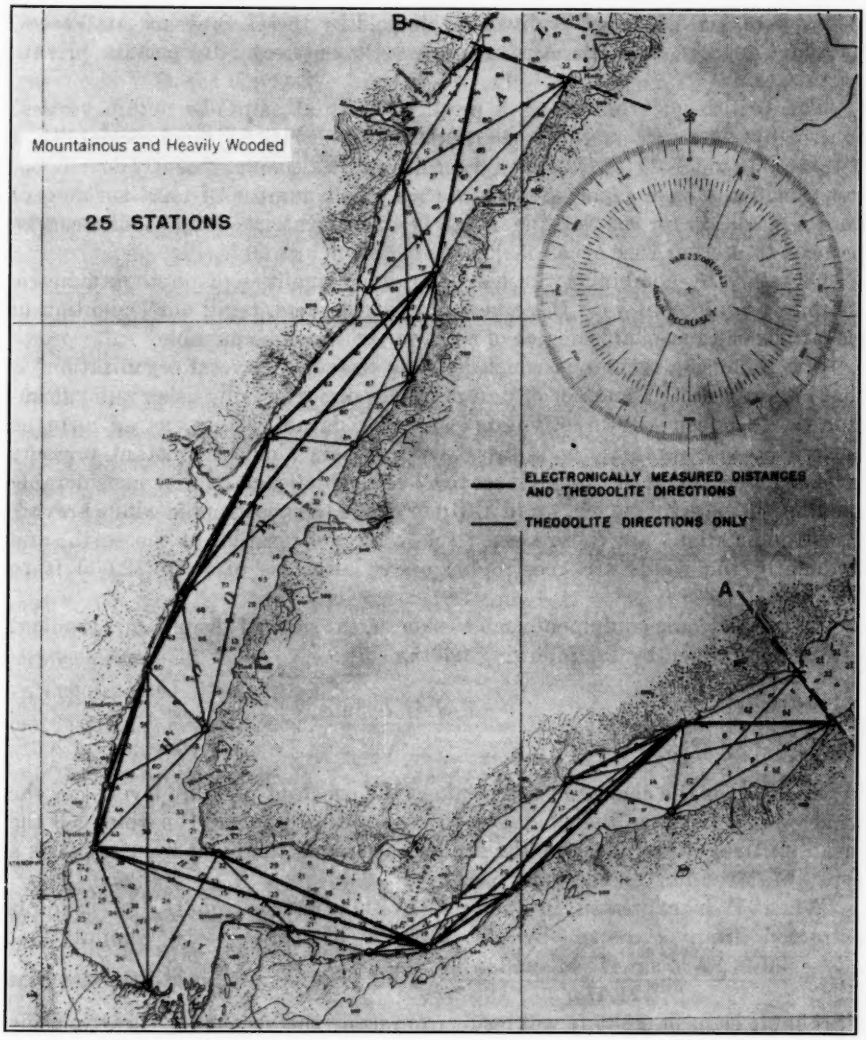

FIG. 5.—TYPICAL CONVENTIONAL SCHEME OF RIVER TRIANGULATION REDUCED BY USING ELECTRONICALLY MEASURED DISTANCES

THE DETERMINATION OF ELEVATIONS BY ELECTRONIC METHODS

Radio altimeter development, including that of narrow-beam instruments, has been advancing. Recording instruments or profile recorders for use in airplanes are also being designed. To the present time (1950) an approach to

the accuracy provided by closely spaced ground control has not been attained, but progress is being made. When the upper air is mapped by meteorological observations from balloons or airplanes simultaneously with the airplane altimeter observations, a moderate degree of accuracy can be obtained. Considerable research is being devoted to this field by the U. S. Army Air Forces, by the Canadian and the Australian governments, and by certain private organizations.

The British government, as a result of early attempts to obtain vertical control by electronic methods, concluded that elevations can be established within ± 10 m (± 33 ft). Using a recording radio altimeter recently developed, the Canadians have reported that, with a small number of level surfaces of known elevation for control, the probable error of intermediate profiles can be reduced to ± 10 ft with occasional errors of as much as 50 ft.

Certainly by combining the height-bridging qualities of photogrammetric compiling equipment with these new profile recorders, rapid determination of elevations of a reasonable degree of accuracy will soon be possible.

One promising technique which is being tested by several organizations is that of establishing a number of datum planes or surfaces by using radio altimeter ties between known elevations and the datum planes, as an airplane located by electronic methods flies between them along a constant pressure level. The gradient of this pressure level can be determined with considerable accuracy if the airplane flies at an altitude where the geostrophic winds prevail. Geostrophic winds are those caused solely by the rotation of the earth, and frequently the winds are geostrophic above altitudes of from 12,000 ft to 15,000 ft.

Using electronic equipment such as shoran, the slope of the pressure gradient can be determined by the following relationship:

$$\Delta H = \frac{V S \sin \alpha \sin \phi}{K} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

in which ΔH is the change in height along the constant pressure level; V is the wind velocity; α is the angle between the aircraft heading and the wind; ϕ is the mean latitude of the line; S is the air distance along the flight line; and K is a constant depending on the units used.

When V is expressed in knots and S in nautical miles, an example extracted from a paper by J. Warner[7] illustrates this computation: $\Delta H = \frac{30 \times 82 \times \sin 47° \times \sin 33° 30'}{21.47} = 46.3$ ft. Mr. Warner estimates that a probable error of ± 35 ft will result from using this method. Clearly, using shoran, the necessary data needed in the computation can be observed to the number of significant places needed for reasonable accuracy. Multiple observations under varying conditions, ties between datum planes, and adjustment of the differences between these datum planes to obtain a consistent series, should reduce the probable error considerably. The method was first

[7] "A Method of Reduction of Line-Crossing Observations in Radar Surveying," by J. Warner, *RPR90*, Council for Scientific & Industrial Research, Div. of Geophysics, Commonwealth of Australia, Radio Laboratory, Sydney, Australia, March, 1950.

tested by the writer, during the Caribbean project of the U. S. Army Air Forces, and additional tests were recommended in the final report. The Canadian government is also using this technique, but no estimate of its accuracy is available in official reports.

Further research, using the pressure-gradient technique, will certainly provide vertical control in many areas where conventional leveling may not be feasible or where it is possible to relax present specifications.

Future Research Required in Electronic Surveying

The accomplishments in electronic surveying, to 1950, have been discussed. However, there is need for further research to obtain:

(1) Better determinations of the velocity of propagation of radio waves;

(2) Better knowledge of the relationship between the index of refraction of moist air and changes in pressure, temperature, and relative humidity; and

(3) Design of instruments specifically for surveying purposes.

Velocity of Radio Waves

The velocity of electromagnetic waves in vacuo is the fundamental yardstick used in electronic distance measurement. At present there is considerable doubt as to the correct value of this constant. The velocity of electromagnetic waves in vacuo has been measured by many observers. The results that have been published since the observation reported by A. A. Michelson in 1879 are listed in Table 1.

TABLE 1.—Measurements of Velocity of Electromagnetic Waves in Vacuo

Year published	Observer	Length (m)	Velocity in vacuo (km per sec)
1879	Michelson[a]	600	299,910 ±50
1882	Newcomb[a]	4,000	299,860 ±30
1902	Perrotin[b]	46,000	299,901 ±84
1906	Rosa and Dorsey[c]	....	299,781 ±10
1924	Michelson[a]	35,000	299,802 ±30
1926	Michelson[a]	35,000	299,796 ± 4
1929	Mittlestaedt[d]	250	299,778 ±20
1935	Michelson, Pease, and Pearson[e]	15,000	299,774 ±11
1937	Anderson[d]	170	299,771 ±15
1940	Huttel[d]	48 to 118	299,768 ±10
1941	Anderson[d]	170	299,776 ±14
1948	Essen[f]	....	299,792 ± 9
1949	Aslakson[g]	....[h]	299,792 ± 1
1950[i]	Bergstrand[d]	9,000	299,792.8 ±0.25

[a] Using rotating mirrors. [b] Using a toothed wheel. [c] By computing the ratio of electrostatic units to electromagnetic units. [d] Using the Kerr cell-photo cell method. [e] Using rotating mirrors in vacuo. [f] Using the resonance in wave guide. [g] Using the shoran method. [h] Forty-seven distances varying from 67 miles to 367 miles. [i] From correspondence between Mr. Bergstrand and the writer.

Obviously this important constant may be uncertain by about 1 part in 20,000. Until greater accuracy is assured in its determination, electronic distance measurement will have proportional uncertainty. However, it is very probable that electronic surveying instruments may prove to offer the best method of determining the velocity of radio waves by comparison with accurately determined distances of varying length. This is particularly true if the long-range instruments such as shoran are improved in accuracy. Shoran errors remain nearly the same irrespective of the distance; therefore the proportional error decreases with an increase in distance.

Index of Refraction of Air

Although the velocity of propagation of radio waves is considered to be constant in vacuo, and independent of the frequency, surveying measurements are made under varying atmospheric conditions. This procedure causes changes in the velocity which must be evaluated for corrective purposes. The relationship between velocity in air, which has a permeability very nearly unity, and in vacuo is expressed by

$$V = V_0/n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

in which V is the velocity in air; V_0 is the velocity in a vacuum; and n is the index of refraction.

Various relationships for the variation of the index of refraction with changes in pressure, temperature, and relative humidity are in use. In general, these expressions take the following form with small differences in the constants:

$$(n - 1)\, 10^6 = \frac{79.5\,(P - e)}{T} + 3.80 \times 10^5 \frac{e}{T^2} \quad \ldots\ldots\ldots\ldots (6)$$

in which P is the total pressure, in millibars; e is the partial vapor pressure, in millibars; and T is the absolute temperature, or 273° plus the centigrade temperature. In extreme cases, the uncertainties in Eq. 6, and in the methods of measuring the quantities involved, may affect the fifth significant place in distance determinations. Thus the evaluation of present long-distance measurements as "approaching the second order" may be improved by a better knowledge of Eq. 6 and by instrumental improvements.

A further uncertainty exists because of a discontinuity in this relationship in the frequency band width which lies between the higher radio frequencies and the optical band. The discontinuity is caused by a change in the dielectric constant of water vapor with respect to frequency in the transition range. Both experimental results and mathematical studies confirm the existence of this discontinuity. The boundary limits have not been closely defined although it is known that the dielectric constant of water vapor remains constant down to wave lengths of the order of 1 mm. A transition then takes place through the infrared region until a new optical value is reached. Therefore, Eq. 6 is valid only for wave lengths longer than 1 mm. Extensive research on the dielectric constant of mixtures of water vapor and air over widely varying frequencies, as well as the improvement of automatic recording meteorological instruments, is of paramount importance to electronic surveying.

Instrumental Design

Considering the fact that, except for the Swedish geodimeter, all research on precise distance measurement has been done with adaptations of instruments designed for military purposes, the results have been remarkable. The shoran instrument used in the Caribbean project contained numerous circuits useless to the surveyor as, for instance, antijamming circuits. It was designed for more liberal tolerances; and, although field modifications were made on that project to increase the accuracy, these modifications did not always eliminate the errors completely. The principal source of error in existing

pulse-type radar instruments arises from a signal intensity error which is a function of the "rise time" of the signal. Unless the time required for the signals to increase from zero to a maximum is reduced to a very small amount, some form of empirical signal-strength correction is needed. This method of correction is unsatisfactory, since many variables difficult to assess are involved. In current studies of shoran an attempt is being made to overcome this difficulty by maintaining voltage gains at a constant level, but at best this is a makeshift solution. The real solution lies in the design of electronic surveying instruments with the "rise time" of the signal greatly decreased. Such studies are currently in progress.

Conclusion

All research in electronic surveying is done either by government organizations or by government development contracts. The success that has attended these efforts is causing the surveying and mapping engineer to realize that his field is undergoing a revolutionary change. Commercial organizations are becoming interested in production, and it is only a matter of time before new electronic surveying equipment will be available for civilian use. The short-distance measuring equipment will no doubt have the wider application, and instruments of this type will effect profound changes in present surveying techniques. Methods of making local precision surveys will be greatly altered. For example, city control surveys will be executed more rapidly and with greater accuracy. The word "trilateration" will become a commonly used surveying term.

The members of the surveying and mapping professions are evincing greater and greater interest in these developments. It is to be hoped that this interest will increase, and that popular support for the research programs in electronic surveying will continue.

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